Impact burial of cylinders in soft marine sediments

by

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Abstract

This paper presents results of experimental deployment of a large instrumented cylinder of variable nose geometry and center of mass offset. Data on three tests series in the Gulf of Mexico are presented and analyzed statistically. The stochastic nature of the problem of the cylinder free-falling through water is outlined and described as an input to the current impact burial prediction package. This predictive package is analyzed in deterministic and stochastic Monte-Carlo frameworks, utilizing the experimentally developed statistical description of all the model input parameters, including the environmental, pertaining to the strength of the sediments, and dynamic, describing the velocities and orientations of the cylinder on impact with the sediment. Significance of the center of mass offset on the behavior of the cylinder is underlined. The importance of accurate knowledge of the sediment shear strength is stressed, as an important factor in predicting penetration burial of large cylinders.

Introduction and background

The main objective of this study is to collect, systematically analyze, and quantify the experimental data on the complex three-dimensional behavior of an instrumented cylinder during freefall in water and sediment. This knowledge is required for estimating the amount of burial of cylindrical objects in soft seafloor marine sediments, and depends on our ability to quantify two main categories of data. One category includes accurate description of the characteristics of the bottom sediments, pertaining to the high strain and high strain rate deformation. This knowledge also needs to reflect the natural variability of these parameters in both spatial and temporal domains. Information on the linear and angular velocities and orientation of the free-falling cylinder at the point of impact with the sediment surface represents the second category of the input information required for the prediction of penetration burial.

Behavior of cylindrical bodies during free-fall has been modeled in the past >1 2@ More recent developments, involving improved and more realistic approaches have been reported >3 4@ Accurate numerical modeling depends in large on the ability to describe the complex three-dimensional dynamic behavior of a cylinder and requires proper accounting for all the forces acting on the falling cylinder. Under

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14. ABSTRACT

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15. SUBJECT TERMS
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ideal conditions, the water column is usually represented as a semi-infinite space with isotropic and constant properties. These properties typically include temperature, salinity, and density. Under these conditions, it has been shown that an idealized cylindrical body, free-falling through the water, could reach a number of stable or quasi-stable motion patterns [1]. Depending on the geometry and the distribution of mass, a range of trajectories can be expected. Several distinct patterns have been experimentally observed and were identified as straight, spiral, flip, flat, and seesaw. A single trajectory may consist of a single pattern or any number and any combination of these motions. Each one of these patterns appears to be stable and, if the cylinder enters a particular pattern, it will remain in this pattern until a sufficient disturbance is applied to the moving body.

In reality, the disturbances are abundant. Heterogeneous state of the ocean, currents changing with depth and time, variations of the water density and salinity are among the most important factors. In order to reproduce a specific experimental trajectory one must have precise knowledge of these factors at the time of deployment. Since this information is often difficult to quantify reliably, and therefore to model accurately, it appears that a more general approach is needed, where these influences, which result in various motion patterns, can be described statistically, with sufficient accuracy. This type of empirical model could provide sufficiently accurate predictions of the freefall of cylinders through the water and penetration burial into the seafloor.

A full scale instrumented cylinder has been released in a realistic field setting. The instrument data is used to characterize the statistics of the dynamic behavior exhibited by this cylinder. In the next section (Experimental Setup) we describe the instrumented cylinder and its deployment. Then, we present the statistical characterization of the observational data (Results). These results suggest that after a short initial period, the freefalling cylinders reach a quasi-stable state, with oscillations about a mean, and we discuss the implications for impact burial prediction (Discussion). Our findings are summarized in the conclusion section.

It is important to underline that the overall goal is to be able to predict the amount of burial of cylindrical bodies in soft seafloor sediments. Thus, the accurate description of the conditions of the cylinder at the point of initial contact with the sediment, in the statistical sense, is crucial to the ability to exercise the sediment component of the impact burial prediction model.

The main objectives of this study are to collect and systematically analyze the experimental data on impact penetration of cylinders in soft mud and to compare these results with model predictions. The predictive analysis includes a stochastic representation of the input parameters, describing the natural variability of the sediment properties of a typical soft cohesive marine deposit and a stochastic evaluation of the output results. The model evaluated includes only the sediment component of the prediction package and utilizes the experimentally measured behavior of a free-falling cylinder at contact with the mudline [5].

The input parameters used in predicting the penetration of a cylinder into the sea-floor sediments are thus divided into two groups – dynamic and environmental. The dynamic parameters include the conditions of the cylinder at the initial contact with the mudline and the beginning of the sediment penetration phase. Since the currently existing predictive software utilizes a simplified two-dimensional approach, the dynamic variables include only the following four components, representing the four degrees of freedom – vertical velocity, horizontal velocity in a plane formed by the cylinder's long axis and the vertical, pitch angle at impact, and angular rotation rate (in the same plane). These dynamic components are stochastic in nature as they result from the entire history of motion through the water column, from the initial release at or above the water surface and until the initial contact with the sea bottom. The statistics of these parameters have been studied and published earlier [5]. The environmental components include a discretized set of layers, of variable thickness, each described by the density and the bearing strength parameters. These values were obtained from the laboratory tests on gravity cores from two locations in the Northern Gulf of Mexico. Experimentally measured burial data were also available from these sites for comparing with the model predictions. These data were obtained during two series of free-fall deployments of a full-scale, instrumented cylinder. The internal instrumentation allowed for recording and storage of the dynamic variables allowing for a subsequent numerical regeneration of a complete dynamic time history of the cylinder, free-falling through the air and water and penetrating into the sediment.

The high variability in all the dynamic parameters of the free-falling cylinder, as was experimentally observed in [5], suggests the following approach. It appears beneficial to separate the randomness of the body motions in one media, the water, from the randomness of those in the sediment, which possesses a set of significantly different characteristics and behaviors, during a typical penetration event. This separation would then allow for a better treatment and incorporation of the media-specific stochastic descriptions into the overall impact burial prediction package. This would also allow for more meaningful evaluation of the overall model performance, based on probability distributions, rather than on single point estimates.

Evaluation of the deterministic performance of the sediment component of the current impact burial prediction model has been presented in [6] by comparing two sets of results of an experimental deployment of a full-size instrumented cylinder (at Corpus Christi, TX and Cocodrie, LA) with model predictions. It was observed that the model performs marginally, at best, with a potential of over- or under-predicting the amount of burial by as much as a factor of 3 or more, especially in softer sediments that produce deeper penetration on impact. This model may nevertheless be found to be able to provide a set of more useful predictions, if used in a stochastic framework, providing added information on the amounts of burial in the form of statistical distributions. This paper presents the results of this study. First, a brief description of the experimental setup and procedures is presented. Then, the stochastic evaluation framework is described and the results of a series of Monte Carlo simulations are presented, followed by a discussion and conclusions.

Experimental setup, equipment, and procedures

Instrumented cylinder and data acquisition

The instrumented cylinder measures 0.53 m in diameter and 2.40 m long, yielding a length to diameter ratio of 4.5. Its weight in air is approximately 10 kN (2250 lbf) and its weight in water (seawater) is about 4.9 kN. The cylinder designed for this study had an adjustable position of the center of mass (CM) relative to the center of volume (CV), along its main axis. Two configurations were tested, representing the Center of Mass Offset (CMO=(CM-CV)/L), of 0.05 and 0.02. On both occasions, the center of mass was located forward of the center of volume. Three different and interchangeable nose shapes were manufactured: blunt, hemispherical, and chamfered. Fig. 1 depicts the instrumented cylindrical shape, strapped to a cradle and with the blunt nose mounted.

The internal instrumentation, placed in the sealed container inside the cylinder, included a set of accelerometers measuring along three orthogonal axes. These accelerometers had three different ranges: 2.5g, 4g, and 10g. Additionally, a tri-axial fiber-optic gyro (FOG) measured the angular rotation rate about three orthogonal axes, collinear with the axes of the accelerometers. The internal instrumentation also included a power source, a signal acquisition and conditioning unit, and a fast access memory storage device. Details of this design can be found in [5, 6, 7].

The data post-processing routines resulted in a set of data that allows analysis of many individual components of the process of free fall and penetration into the sediment. Fig. 2 (a) represents an example of a typical visualization of the calculated trajectory of the cylinder during free fall. Fig. 2 (b) shows the sediment penetration phase of the trajectory only, starting at the initial contact with the seafloor and until the cylinder comes to a complete stop, embedded in the sediment.

Testing procedures

The data reported in this study was obtained during four cruises. These cruises included the January 2002 cruise on board R/V Pelican, in the vicinity of Cocodrie, LA (labeled "P02" hereafter), May 2002 cruise on board R/V Gyre, in the vicinity of Corpus Christi, TX ("G06"), and two cruises on board R/V Pelican near East Bay, LA in June 2003 ("P03"), and May 2004 ("P04").

Each of these trips included a series of drops with varying cylinder nose configurations, CMO, and initial conditions. The first three cruises deployed a cylinder with CMO=0.05 and the last one, "P04" – with CMO=0.02. Release medium was also varied with some of the cylinder deployments performed from the air, usually only a small height above the water surface, and some others released from the fully submerged position of just below the water surface. Additionally, the initial inclination (pitch) was changed by using different strapping: horizontal and at 31 degrees nose down during P02, G06, and P03 cruises and 4.5° nose down during the P04 cruise. **Table 1** summarizes the number of tests performed, broken down by the nose shape, release medium, inclination, and CMO. Details of the deployment procedures have been reported elsewhere [5, 6].

The accurate determination of the dynamic parameters of the falling cylinder at the point of contact with the sediment was required for implementation of the predictive algorithm describing penetration into the mudfloor. The parameters required for input included two components of linear velocity, vertical and horizontal, pitch, and angular velocity in the vertical plane of the cylinder at the instant of initial contact with the sediment.

Results of the analysis presented here are sensitive to the accurate determination of the actual initial contact of the falling cylinder with the sediment. Selection of this point of impact can be done using two different methods. One is based on the diver observed elevation of the cylinder at rest, embedded in the sediment, and the other is based solely on the observed variations of various dynamic parameters of the cylinder as it is falling through the water and penetrating into the mud. It was decided to utilize the first method, relying on the diver measured elevations to pick the time of contact of the cylinder with the seafloor. This method appears to the authors to be more self-consistent producing more reliable results especially in softer sediment deposits. Details of the reasoning used in making this decision are given in [6].

Experimental observations

Behavior in the water column

The inherent stochastic nature of the dynamic behavior of a cylinder, free-falling though water, is evident in Fig. 3. The figure shows a wide scatter (in the vertical component of the velocity vector) about a mean that appears to stabilize after less than one second from the moment of release. All releases were done from less than one meter above or below the water surface. This travel time corresponds to a maximum water depth of about 3.5m. From this point on, the mean vertical velocity remains reasonably constant at about 3.5-4.0 m/s. The dependence of this pseudo-terminal velocity was examined as a function of the cylinder configuration, *i.e.* nose shape and the center of mass offset (CMO), as well as the release conditions. It was already shown [5, 6] that the initial conditions (at release) do not affect the behavior of the cylindrical body beyond the depth of 3.5m. Fig. 4 shows the variation of: (a) means and (b) standard deviations of vertical velocity for drops with blunt nose; and Fig. 5 shows these for the chamfered nose. Fig. 6 shows the same variation of the vertical velocity (a), and pitch (b) with time, grouped by the value of the CMO. Analysis of these figures, as well as behavior of other dynamic parameters (remaining components of linear and angular velocities) finds that the center of mass offset plays the most prominent role in the behavior of the full-size cylinder in free fall. Similar findings were reported for very small cylindrical shapes in [1]. Fig. 6 shows a difference of about 0.5 m/s in values of the mean vertical velocity, calculated for all drops with two CMOs tested. The standard deviation of the smaller offset of the center of mass is indicative of the fact that the more centrally-weighted cylinder assumes a position of broadside to the direction of fall quicker and maintains it with higher stability. This is also evident from Fig. 6, observing the behavior of pitch with time. This relatively more stable orientation, with slightly decreased vertical velocity of fall, however, results in larger lateral travel of the cylinder fom the point of release and until embedment in the mudfloor. Fig. 7 shows that, although on average the lateral travel is similar, the standard deviation is twice as high, resulting in the increased likelihood of the cylinder traversing larger lateral distances during the freefall.

Behavior in the sediment

The behavior of the cylinders upon entry into the soft sediments is presented in Figs. 8 and 9. The instrumented cylinder buried the most at P03, to an intermediate depth at G06, and the least at the P02 location, correlating well with the averaged values of undrained shear strength, *Su*, of ~3, ~5, and ~15kPa for sites P03, G06, and P02, respectively. This observation re-iterates the importance of the sediment undrained shear strength in driving the depth of penetration relationship. Also indicated is the influence of the cylinder nose shape on penetration and the rate of decay of the vertical velocity. It appears that the hemispherical shapes yielded the fastest decrease in the vertical momentum in what appears to be due, primarily, to the rapid redirection of the momentum from the vertical to the horizontal direction. This redirection is achieved because of the deflection of trajectory of the falling cylinder along its nose's spherical surface during impact. This results in a doubling of deceleration values along the vertical axis (Fig. 9 (b)).

Modeling penetration: deterministic and stochastic analyses

The modeling of the cylinder penetration into soft sediments proceeded according to two types of analyses: deterministic and stochastic. In the deterministic analysis, the experimentally measured orientation and dynamics of a cylinder served as an input to the predictive model, together with the sediment density and undrained shear strength measured on gravity cores, recovered from the vicinity of each drop. The deterministic prediction results for the P02 and the G06 cruises have been presented before [6]. These results are compared here with the prediction of the third (P03) cruise. The sediment data on the last cruise (P04) was not available at the time of writing of this paper. Fig. 10 shows the experimentally measured (a) and predicted (b) vertical penetration distance of the cylinder. The model performance is estimated to be reasonably adequate, especially for the softer sediments (P03), in the mean sense. The percent difference in estimating the final penetration distance after impact was found to be 37, 22, and 10% for P02, G06, and P03, respectively. One needs to remember that the comparisons made here are only true in the mean sense and that the large standard deviations, indicated by the error-bars in Fig. 10, are indicative of the generally limited accuracy of the deterministic predictions. Efforts are currently underway to improve the performance of the prediction algorithm, especially pertaining to the performance in harder sediments. Added meaning may also be obtained when the predictive model is exercised in a stochastic framework.

In the stochastic part of our analysis, the variability in the two sets of parameters (dynamic and environmental) was modeled by using a random sampling technique, drawing values from a set of probability density functions built from the experimental data. The details of this technique are presented in [8]. The input data included vertical and horizontal velocities (in the plane formed by the cylinder long axis and the vertical), the impact angle, and the angular rotation rate. These parameters were taken at the point of sediment contact from the two experimental sets of data under consideration. The environmental parameters included 13 sediment layers, each characterized by its density and bearing strength. All parameters were assumed to be Gaussian for the purpose of this study and were thus represented by their means and variances, averaging over each entire site considered.

A Monte Carlo simulation technique was used to propagate the uncertainty from the input to the output parameters. In order to compare the output distributions with the experimental data, the latter was represented with its Gaussian approximation, as was the input data. Limitations on the number of data points available to construct a distribution are known (especially in the case of sites P02 and G06) and will need to be treated with caution.

Gaussian distributions of the diver measured height of cylinder exposed and final pitch (while at rest in the mud) are compared with those predicted using the Monte-Carlo algorithm in Figs. 11, 12 and 13 for sites P02, G06 and P03, respectively. The model distributions were represented by 1,000 runs. The results show that the height protruding is overestimated somewhat for those mines that penetrated deeper at P02 (Fig. 11a), with the predictions for G06 covering rather reasonably. Again, one needs to remember here of the limited number of samples in experimental distributions and refrain from over-interpretation. The experimental distributions of the pitch angle are modeled reasonably well also for the site with softer sediments (P03 – Fig. 13). Both the height protruding and especially the pitch are modeled rather well for this softer location (P03). Another variable of interest, percent area exposed is analyzed in Fig. 14 (for P02 and G06 locations) and Fig. 15 for the P03 site. Predictions of burial for the P02 and the G06 sites are somewhat more accurate in this case, with relatively good approximations for G06, the two sites with the stiffer sediments. Results for the P03 site show a slight under-prediction in the surface area exposed for the lower range of values and a small over-prediction for the higher ones. Relatively lower performance of the prediction model in this case (Fig. 15a,b) could be in part attributable to the very selection of the criterion variable – percent area exposed – which is not a continuous variable. The softest site had the most number of cylinders penetrating to full burial which introduces some inaccuracies in comparisons with the simulated data. In general, the model performed relatively well in this stochastic framework, for all three sites considered

It is acknowledged that there are deficiencies in representing the input variables using Gaussian approximation. The amount of data for the first two sites examined is small, which makes the comparisons between the experimental and measured data difficult. Additionally, the normal curve may not represent all of the input parameters very accurately. It was chosen as the first approximation with an overall goal of developing a stochastic model evaluation. Other distributions may be examined and could potentially represent the experimentally measured data better. One such evaluation could be done using β- or γ-distributions. The main attractiveness of this approach lies in the asymmetric shape as well as limited extent $(0,\infty)$ or $(0,1)$, unlike the Gaussian distribution that also involves values of no physical significance, outside of the range of interest (or possibility) for some of the input and output variables.

Discussion and conclusions

This paper presents results of experimental test series on impact burial of large cylinders with variable nose shape and center of mass offset. Statistical analysis of the behavior of the cylinder in water and sediment was presented. It was observed that the center of mass offset plays an important role in determining the dynamics of the body in freefall. Influences of nose shapes were considered effects of second order in the water column. In the sediment, the effects of the nose shape were found to produce a somewhat larger effect on the overall penetration burial.

A numerical study, employing deterministic and Monte Carlo algorithms for predicting the amount of impact burial of cylinders is compared to the experimentally observed values. A statistical framework for analyzing the model results and comparison with the experimental data was described. It was observed that the model performs relatively well in both deterministic and stochastic frameworks, producing reasonable estimates of burial in most cases. The model produced best results in predicting burial of cylinders in softer sediments with greater overall penetrations. The largest amount of discrepancy between the experimentally measured and modeled amount of height buried and the final pitch of the cylinder embedded in mud was produced for the hardest of all three sites investigated. It was also observed that the use of the percent surface area buried as a comparative parameter between measured and predicted values may sometimes introduce errors due to the discontinuous nature of its significant range, only between 0 and 100%.

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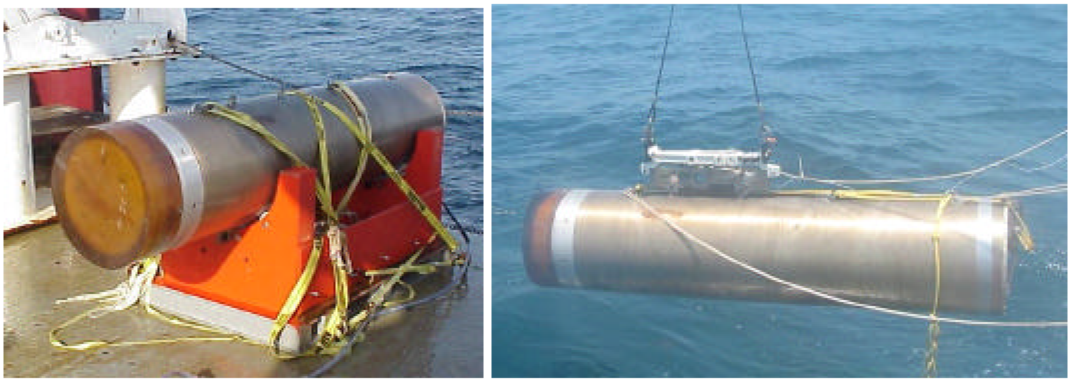
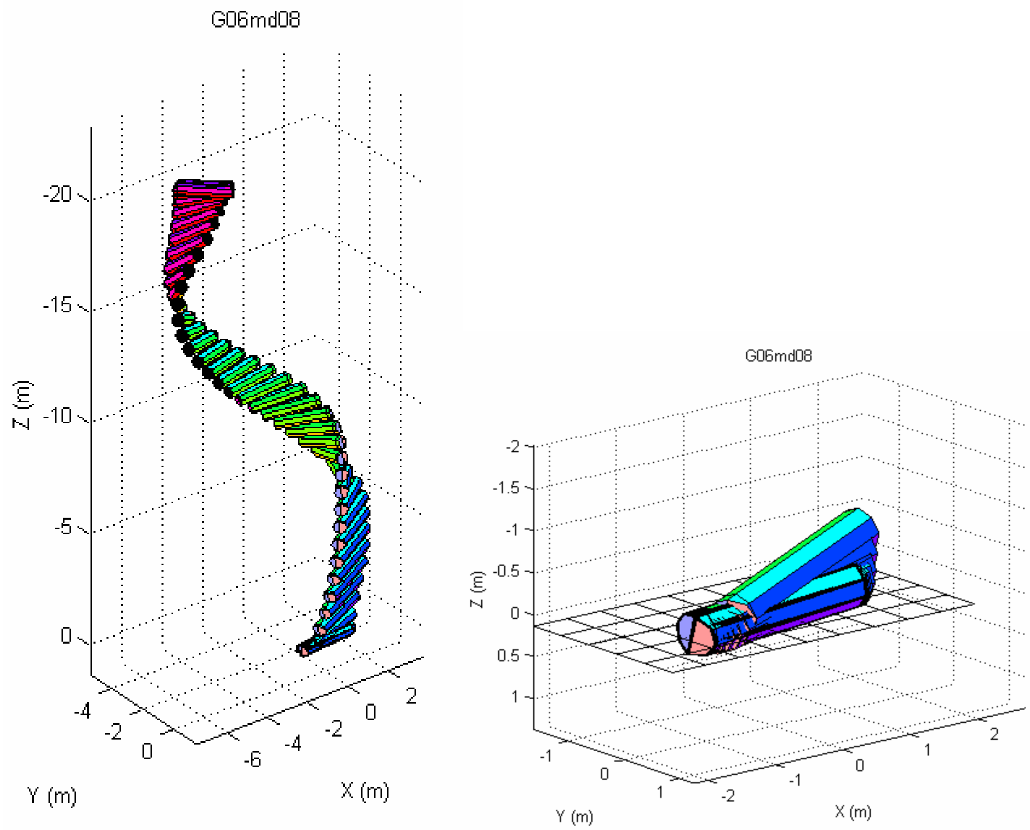
Table 1 Tests, sorted by nose shape, release angle, and center of mass offset

Blunt nose	48
Hemispherical nose	42
Chamfered nose	23
Air released	42
Water released	71
Horizontal releases	28
Releases at 31 deg.	30
Releases at 4.5 deg.	55
(CM-CV)/L = 0.05	58
(CM-CV)/L = 0.02	55



(a) (b)

Fig. 1. General view of the instrumented cylinder with the blunt nose attached in the cradle (a) and before release (b)



(a) **(b)**

Fig. 2. A typical calculated trajectory of the instrumented cylinder in free-fall (a), and a sediment penetration portion only (b). The cylinder is outfitted with the chamfered nose.

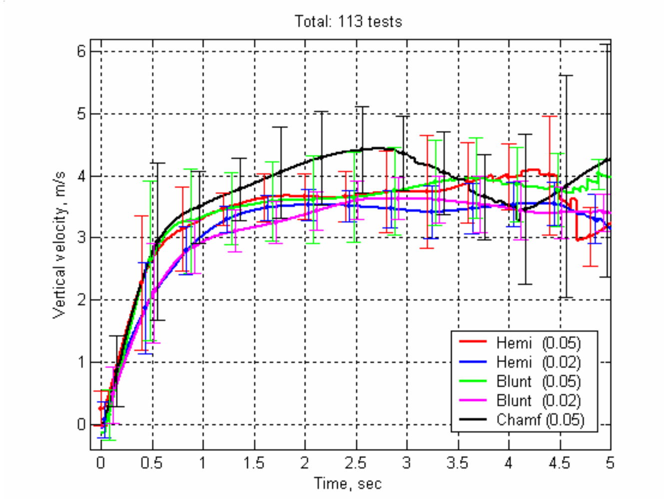
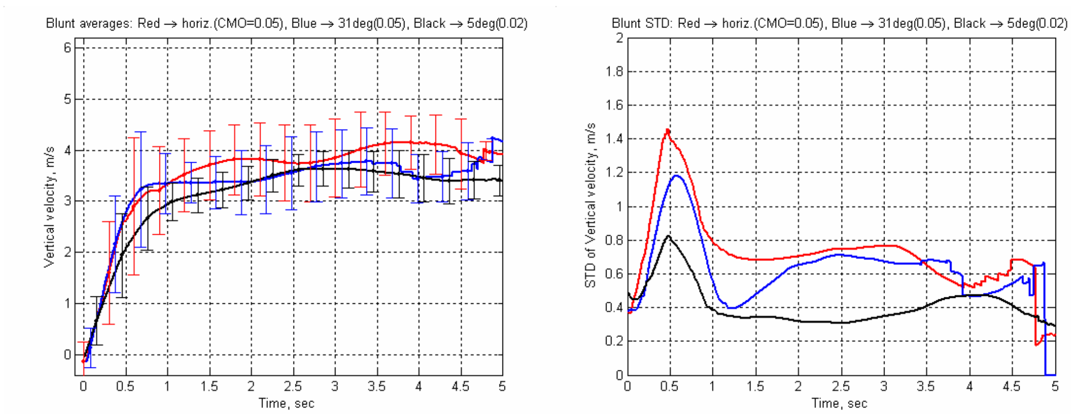
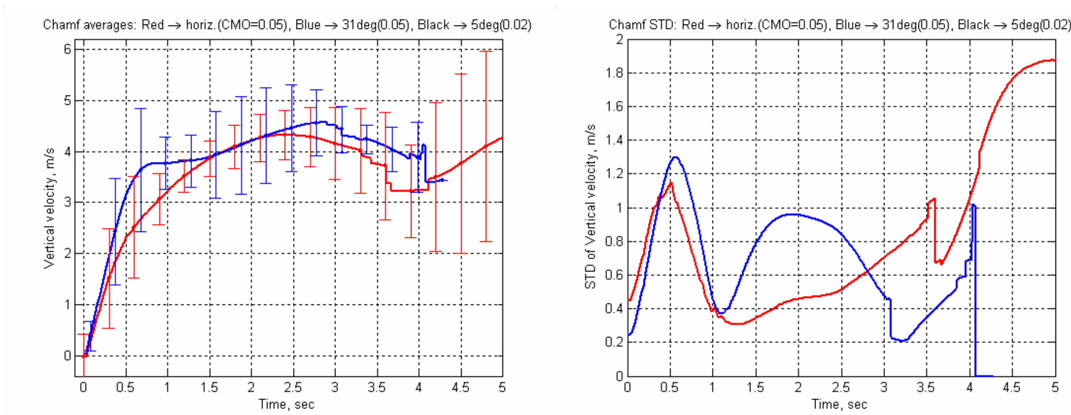


Fig. 3. Averages and standard deviations plotted as error-bars for all drops, sorted by nose shape and center of mass offset



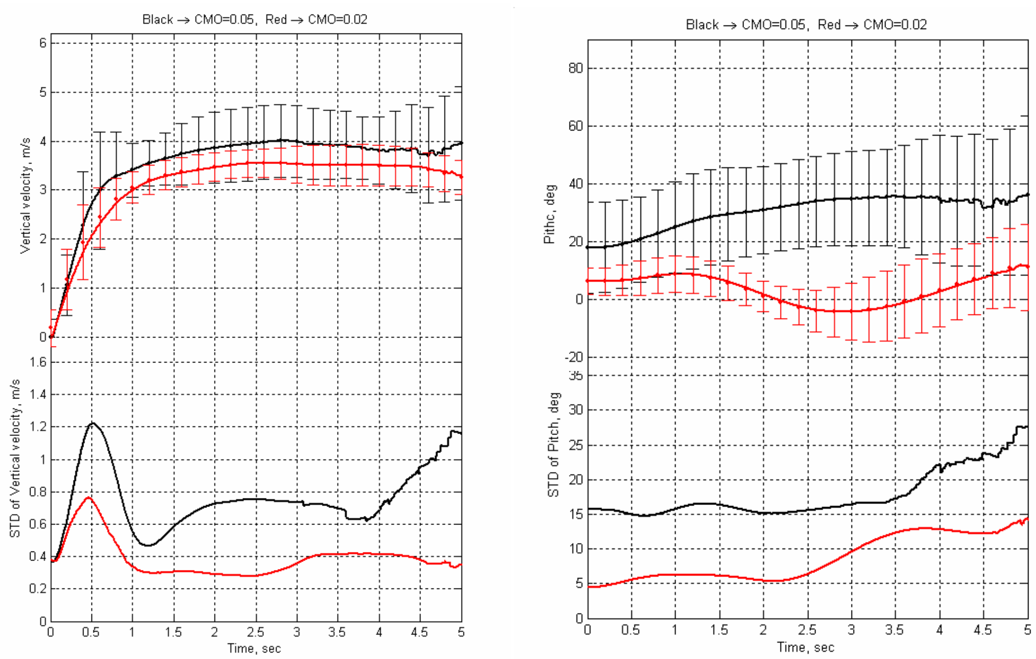
(a) **(b)**

Fig. 4. Means (a) and standard deviations (b) of the vertical velocity time series for cylinder deployments with blunt nose, sorted by release angle



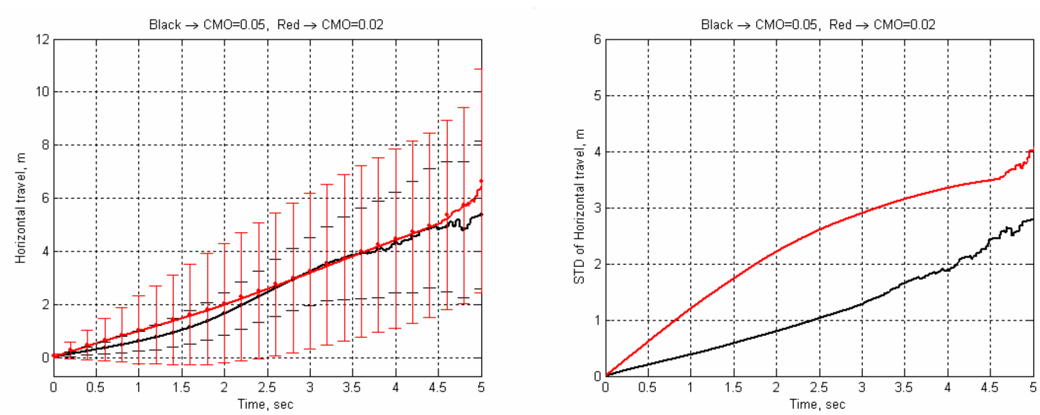
(a) **(b)**

Fig. 5. Means (a) and standard deviations (b) of the vertical velocity time series for cylinder deployments with chamfered nose, sorted by release angle



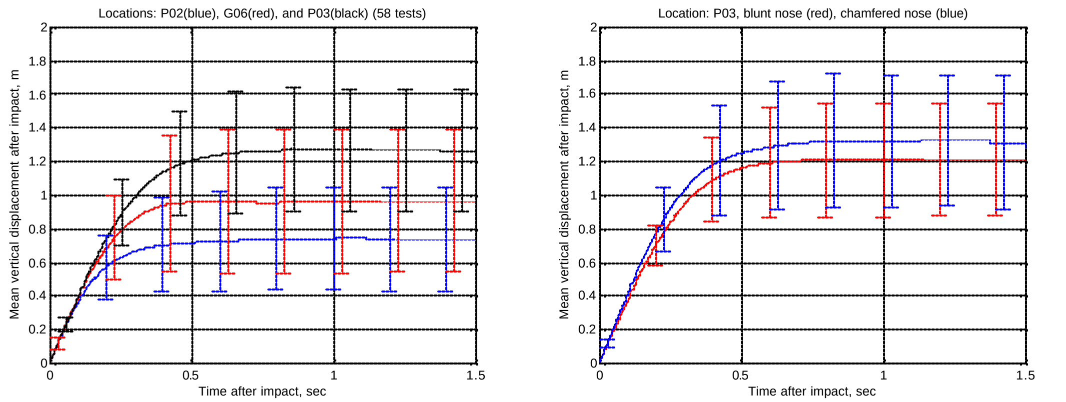
(a) **(b)**

Fig. 6. Mean and standard deviation of the vertical velocity (a) and the pitch angle (b), sorted by the CMO (center of mass offset)



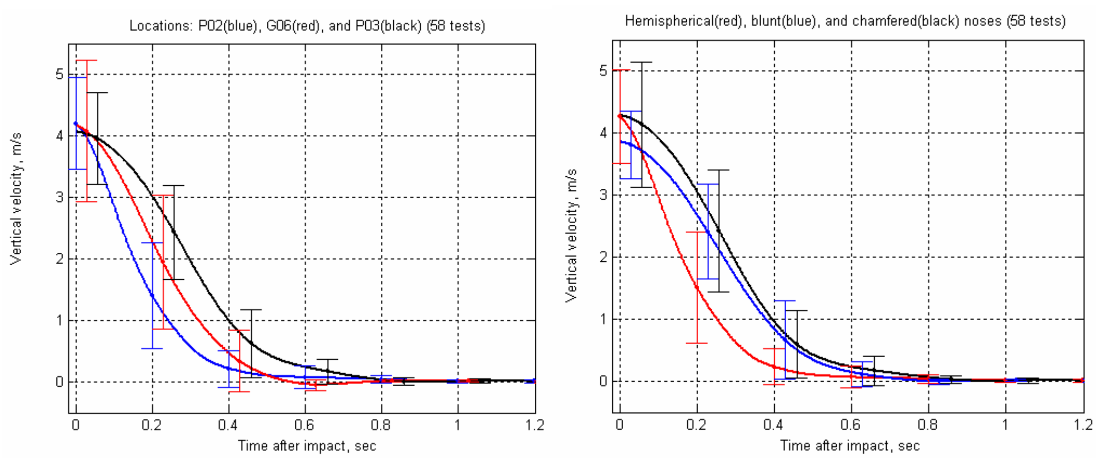
(a) **(b)**

Fig. 7. Mean (a) and STD (b) of the lateral travel of the instrumented cylinder sorted by the offset of the center of mass



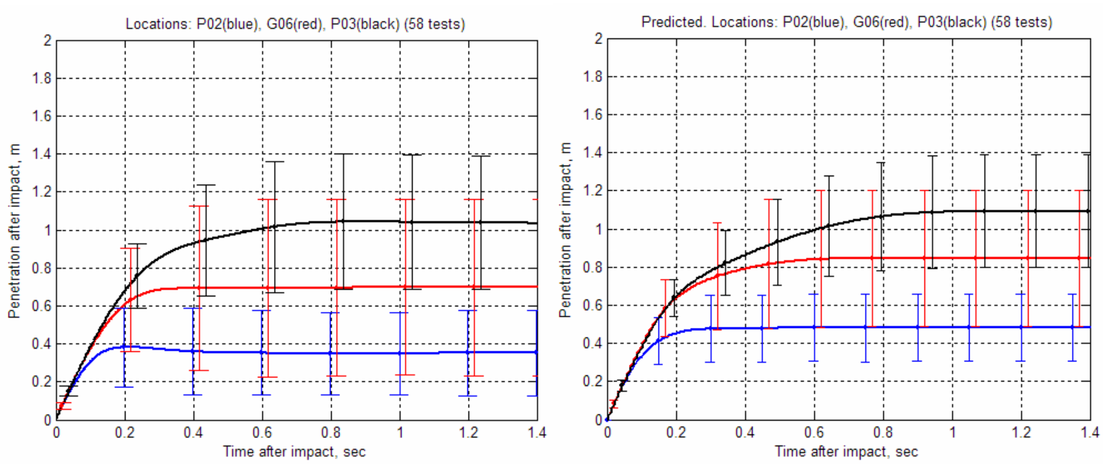
(a) **(b)**

Fig. 8. Behavior in the sediment: mean vertical displacement after impact, sorted by site (a) and by nose type (b)



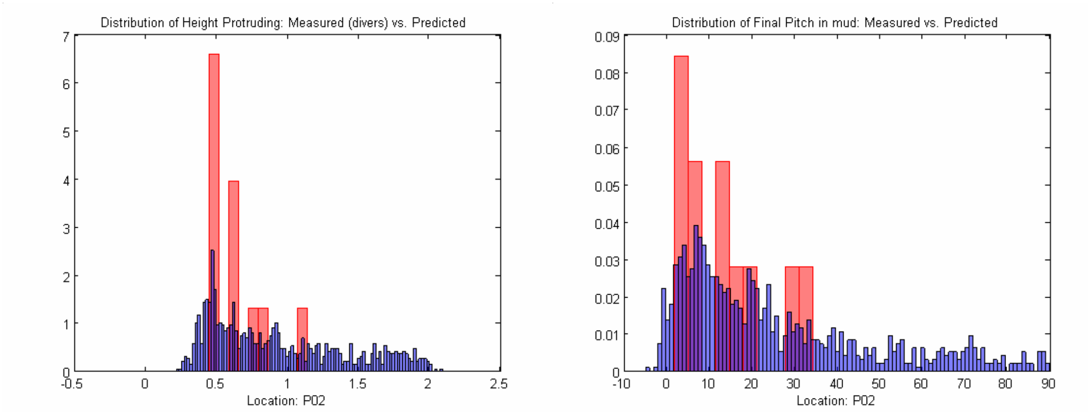
(a) **(b)**

Fig. 9. Behavior in the sediment: vertical velocity after impact, sorted by site (a) and by nose type (b)



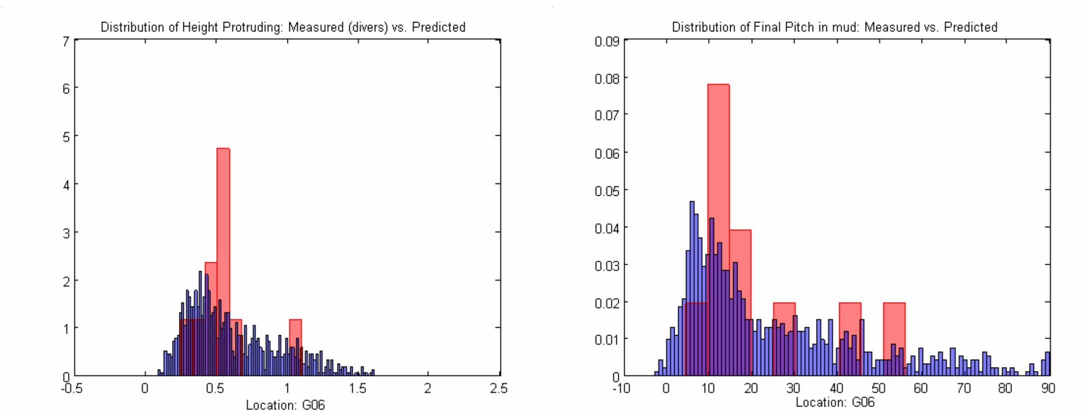
(a) **(b)**

Fig. 10. Behavior in the sediment: experimentally measured (a) and predicted (b) values of the penetration distance after impact



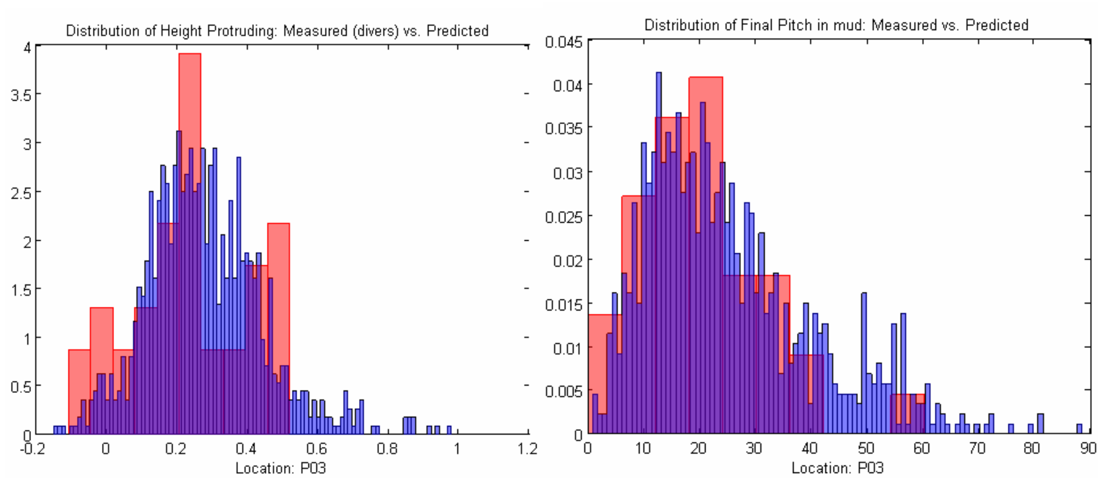
(a) **(b)**

Fig. 11. Diver measured vs. Monte-Carlo simulated distributions of height protruding (a) and final pitch (b) for a test location near Cocodrie, LA (P02)



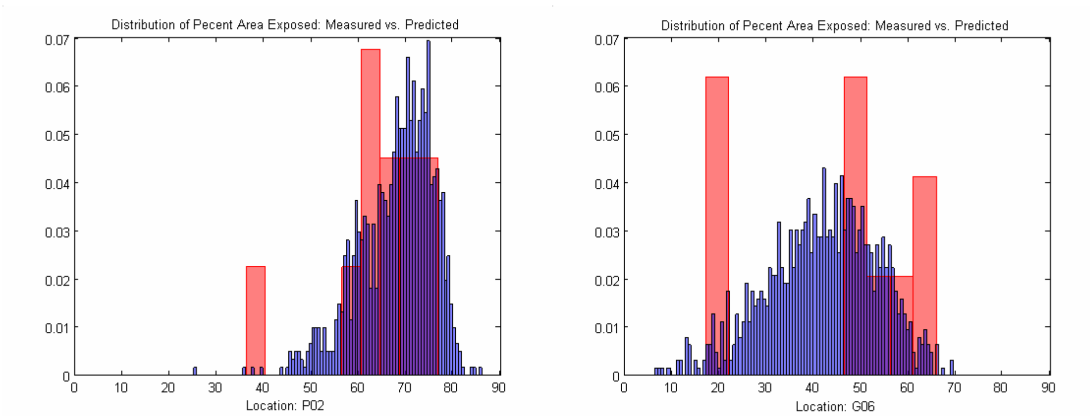
(a) **(b)**

Fig. 12. Diver me asured vs. Monte-Carlo simulated distributions of height protruding (a) and final pitch (b) for a test location near Corpus Christi, TX (G06)



(a) **(b)**

Fig. 13. Diver measured vs. Monte-Carlo simulated distributions of height protruding (a) and final pitch (b) for a test location near East Bay, LA (P03)



(a) **(b)**

Fig. 14. Diver measured vs. Monte-Carlo simulated distributions of percent surface area exposed for a test location near Cocodrie, LA (P02), (a) and near Corpus Christi, TX (G06), (b)

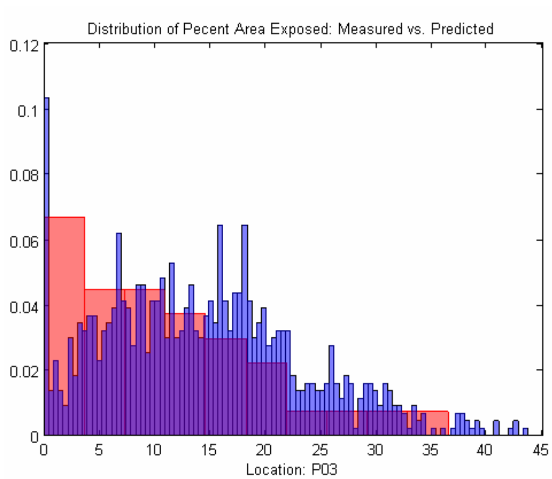


Fig. 15. Diver measured vs. Monte-Carlo simulated distributions of percent surface area exposed for a test location near East Bay, LA (P03)